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DERIVATION OF THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD [IGRF (10/68)]

A REPORT TO IAGA COMMISSION II WORKING GROUP 4

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DECEMBER 1968

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

This report summarizes the testing of the various magnetic field models against the available World Magnetic Survey data and describes the method by which the first International Geomagnetic Reference Field [IGRF(10/68] was derived. The IGRF(10/68) was composed of contributions of the field models derived by: Goddard Space Flight Center, Air Force Cambridge Research Laboratories, Royal Greenwich Observatory, Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN), and the U. S. Coast and Geodetic Survey.

IGRF(10/68) is a set of 80 internal spherical harmonic coefficients and their first time derivatives epoch 1965.0 referenced to a sphere 6371.2 km radius. The root-mean-square residuals to surface and airborne magnetic survey data taken during the interval 1961 through 1965 average about 200γ. The rms deviations from selected COSMOS-49 (1964.7) and POGO (1965.8 - 1967.9) total field satellite observations range from 30 to 60γ.

Introduction

This is to summarize some of the computations that took place at the IAGA Symposium in Washington, D. C., October 22-25, 1968 that led to the resolution by the Working Group on the Analysis of the Geomagnetic Field (Reporter, A. J. Zmuda) to propose a particular International Geomagnetic Reference Field. The basic requirements established by Dr. Zmuda following the discussion at previous meetings was that the IGRF would consist of no more than 80 spherical harmonic coefficients of internal origin epoch 1965.0, with each having a first time derivative. These coefficients were to be true spherical harmonics in describing the field as opposed to those "quasi-spherical" coefficients resulting from derivations neglecting the oblateness of the earth. Further, only sets of coefficients submitted to the Working Group on or prior to March 15, 1968 were to be considered.

These sets of spherical harmonic coefficients are given in Table 1. They are each updated to 1965.0, and limited to an n* (maximum degree n and order m) of eight. Of the sets given, all except (g) and (h) meet the requirement of taking into account the oblateness of the earth in their derivation. Most of the field descriptions are to appear in the WMS volume to be published. However, a few have been published separately as follows:

EPOCH = 1965.0 GSFC(12/66) SET 1

N	M	G	H	GT	HT
1	0	-30333	0	13.7	0.0
1	1	-2117	5759	9.3	-3.9
2	0	-1660	0	-24.1	0.0
2	1	2997	-2002	-0.2	-14.0
2	2	1561	119	-5.8	-16.7
3	0	1299	0	-1.5	0.0
3	1	-2043	-397	-10.8	5.7
3	2	1289	240	2.4	2.5
3	3	847	-167	-6.8	-6.6
4	0	957	0	1.5	0.0
4	1	807	149	0.7	-2.2
4	2	495	-274	-1.7	0.1
4	3	-394	11	0.7	1.7
4	4	249	-280	-3.5	-6.8
5	0	-224	0	1.8	0.0
5	1	359	15	0.6	2.0
5	2	247	126	3.7	1.6
5	3	-29	-128	-0.0	-2.6
5	4	-161	-106	-0.5	0.5
5	5	-52	81	2.0	-0.2
6	0	47	0	-0.4	0.0
6	1	62	-11	0.9	0.1
6	2	4	105	0.9	0.0
6	3	-225	70	2.6	2.6
6	4	2	-30	0.8	-1.3
6	5	-1	-12	0.1	0.5
6	6	-107	-9	0.3	0.8
7	0	69	0	-0.6	0.0
7	1	-56	-59	-0.4	-1.0
7	2	0	-27	-1.6	0.1
7	3	11	-6	-0.9	0.5
7	4	-24	11	0.0	0.8
7	5	-7	22	-0.7	-0.4
7	6	15	-20	-0.2	0.6
7	7	0	-17	-0.7	1.0
8	0	10	0	0.4	0.0
8	1	9	3	0.5	-0.6
8	2	0	-13	1.9	-0.3
8	3	-10	4	-0.1	0.1
8	4	-4	-20	0.4	-0.8
8	5	5	5	-0.1	0.0
8	6	-6	22	0.5	0.1
8	7	12	-3	-0.2	-0.4
8	8	5	-19	-0.5	-0.4

TABLE 1(a)

EPOCH = 1965.0 AFCRL(3/68)

N	M	G	H	GT	HT
1	0	-30339	0	12.0	0.0
1	1	-2133	5774	6.7	-0.9
2	0	-1657	0	-27.6	0.0
2	1	2993	-2016	-0.2	-15.9
2	2	1579	140	-3.6	-15.4
3	0	1302	0	0.3	0.0
3	1	-2039	-409	-10.2	5.0
3	2	1290	239	1.2	2.1
3	3	855	-195	-6.8	-10.9
4	0	965	0	0.7	0.0
4	1	807	142	0.8	-1.4
4	2	495	-286	-0.3	-1.4
4	3	-391	1	-0.5	2.6
4	4	269	-269	-1.0	-4.4
5	0	-220	0	3.3	0.0
5	1	351	26	0.6	2.2
5	2	239	129	2.6	2.3
5	3	-26	-118	0.4	-1.8
5	4	-151	-117	1.6	-1.8
5	5	-44	80	4.0	-0.1
6	0	47	0	-1.2	0.0
6	1	56	-16	-1.0	-0.5
6	2	7	104	0.5	0.1
6	3	-237	68	1.1	1.9
6	4	1	-27	0.4	0.2
6	5	-12	-8	-2.7	0.6
6	6	-103	-17	0.4	-0.4
7	0	75	0	0.2	0.0
7	1	-53	-52	-0.3	-0.6
7	2	-3	-30	-1.0	-0.8
7	3	20	-10	0.8	0.9
7	4	-27	4	-0.5	-0.4
7	5	-11	20	-0.8	-0.4
7	6	6	-16	0.7	1.7
7	7	-12	-15	-2.2	1.3
8	0	9	0	-0.2	0.0
8	1	5	10	0.3	-0.3
8	2	-5	-14	0.0	-0.2
8	3	-15	13	-0.7	-1.0
8	4	-8	-15	-0.9	-0.4
8	5	3	2	-0.2	-0.4
8	6	-7	19	-0.4	-0.2
8	7	9	-4	-1.7	-1.3
8	8	8	-13	-0.9	-0.7

TABLE 1(b)

EPOCH = 1965.0 RGO(3/68)-2 (MALIN)

N	M	G	H	GT	HT
1	0	-30350	0	17.0	0.0
1	1	-2115	5770	9.0	0.0
2	0	-1640	0	-24.0	0.0
2	1	2979	-2000	-1.0	-12.0
2	2	1585	115	2.0	-18.0
3	0	1279	0	0.0	0.0
3	1	-2008	-425	-10.0	5.0
3	2	1289	241	-1.0	1.0
3	3	862	-156	-1.0	-9.0
4	0	940	0	-1.0	0.0
4	1	792	161	0.0	1.0
4	2	484	-280	-4.0	1.0
4	3	-389	11	1.0	3.0
4	4	259	-254	-3.0	-3.0
5	0	-207	0	1.0	0.0
5	1	367	18	0.0	2.0
5	2	239	133	3.0	2.0
5	3	-28	-122	-1.0	-2.0
5	4	-166	-97	-1.0	1.0
5	5	-64	75	1.0	0.0
6	0	39	0	0.0	0.0
6	1	55	-17	0.0	-2.0
6	2	2	107	1.0	1.0
6	3	-233	58	2.0	2.0
6	4	7	-31	0.0	-1.0
6	5	3	-16	0.0	0.0
6	6	-112	-10	-1.0	1.0
7	0	77	0	0.0	0.0
7	1	-47	-46	0.0	0.0
7	2	2	-25	0.0	0.0
7	3	12	-10	0.0	0.0
7	4	-28	8	0.0	0.0
7	5	-12	24	0.0	0.0
7	6	15	-22	0.0	0.0
7	7	5	-21	0.0	0.0
8	0	6	0	0.0	0.0
8	1	13	-4	0.0	0.0
8	2	-6	-7	0.0	0.0
8	3	-17	1	0.0	0.0
8	4	2	-16	0.0	0.0
8	5	10	5	0.0	0.0
8	6	-5	24	0.0	0.0
8	7	12	4	0.0	0.0
8	8	6	-15	0.0	0.0

TABLE 1(c)

EPOCH = 1965.0 IZMIRAN(3/68)

N	M	G	H	GT	HT
1	0	-30358	0	18.6	0.0
1	1	-2147	5706	7.7	-2.5
2	0	-1630	0	-25.1	0.0
2	1	3000	-2015	0.1	-9.8
2	2	1552	201	-1.2	-15.8
3	0	1297	0	0.8	0.0
3	1	-2035	-391	-8.9	4.3
3	2	1289	264	0.0	0.7
3	3	758	-229	-1.7	-5.6
4	0	976	0	0.2	0.0
4	1	814	138	0.3	1.4
4	2	486	-308	-2.3	0.9
4	3	-388	-1	0.0	2.5
4	4	266	-174	-1.3	-1.6
5	0	-242	0	0.6	0.0
5	1	344	-6	0.3	0.4
5	2	262	102	1.1	1.4
5	3	-5	-99	-0.4	-1.2
5	4	-174	-106	-0.7	0.2
5	5	-42	52	0.1	0.2
6	0	62	0	-0.5	0.0
6	1	68	-18	0.3	-0.4
6	2	6	112	0.7	0.2
6	3	-226	76	1.3	0.9
6	4	2	-58	0.4	0.0
6	5	-20	5	0.0	0.0
6	6	-160	-30	0.0	0.0
7	0	64	0	0.0	0.0
7	1	-55	-73	0.0	0.0
7	2	4	-27	0.0	0.0
7	3	3	-14	0.0	0.0
7	4	-19	12	0.0	0.0
7	5	-8	31	0.0	0.0
7	6	13	-16	0.0	0.0
7	7	-10	-13	0.0	0.0
8	0	16	0	0.0	0.0
8	1	10	4	0.0	0.0
8	2	-9	-22	0.0	0.0
8	3	-16	2	0.0	0.0
8	4	-6	-11	0.0	0.0
8	5	18	-2	0.0	0.0
8	6	8	26	0.0	0.0
8	7	16	-10	0.0	0.0
8	8	8	-8	0.0	0.0

TABLE 1(d)

EPOCH = 1965.0 POGO(3/68)

N	M	G	H	GT	HT
1	0	-30338	0	26.2	0.0
1	1	-2112	5770	4.7	-6.1
2	0	-1661	0	-23.3	0.0
2	1	2999	-2011	2.3	-9.0
2	2	1595	123	11.8	-8.8
3	0	1302	0	-8.2	0.0
3	1	-2043	-406	-9.3	10.7
3	2	1299	239	-0.8	2.6
3	3	856	-160	-11.0	0.8
4	0	955	0	-0.3	0.0
4	1	803	152	-1.5	4.3
4	2	478	-275	-6.0	-0.8
4	3	-382	15	-6.3	2.9
4	4	254	-230	-3.3	-14.2
5	0	-222	0	3.8	0.0
5	1	361	19	-0.5	-1.0
5	2	247	127	1.2	1.1
5	3	-33	-126	1.8	-4.5
5	4	-168	-98	-3.5	0.7
5	5	-54	76	1.2	-5.3
6	0	46	0	-0.3	0.0
6	1	62	-11	0.9	-1.0
6	2	11	106	2.1	-0.5
6	3	-233	68	5.7	0.5
6	4	3	-45	0.6	2.0
6	5	-12	3	2.1	0.8
6	6	-144	-25	-3.9	0.1
7	0	72	0	-0.9	0.0
7	1	-53	-63	0.0	-0.5
7	2	3	-27	0.1	0.8
7	3	14	-8	-0.8	0.5
7	4	-22	7	2.5	1.2
7	5	-6	24	0.4	1.2
7	6	12	-19	0.2	-0.6
7	7	-10	-19	1.4	1.9
8	0	10	0	0.4	0.0
8	1	3	10	0.4	0.4
8	2	-4	-13	0.5	-0.2
8	3	-10	8	-1.5	-0.5
8	4	-5	-13	-0.6	-1.6
8	5	14	-1	-0.7	0.0
8	6	5	26	1.5	0.1
8	7	15	-10	0.4	-0.1
8	8	9	-11	-2.6	1.1

TABLE 1(e)

EPOCH = 1955.0 AFCRL(11/67)

N	M	G	H	GT	HT
1	0	-30332	0	12.4	0.0
1	1	-2137	5791	6.3	0.0
2	0	-1658	0	-27.5	0.0
2	1	2992	-2002	-0.3	-13.8
2	2	1573	142	-3.0	-13.9
3	0	1306	0	0.3	0.0
3	1	-2035	-404	-9.7	4.0
3	2	1294	250	1.4	3.3
3	3	866	-184	-4.5	-12.0
4	0	954	0	-0.3	0.0
4	1	812	139	0.9	-1.9
4	2	491	-288	0.4	-2.1
4	3	-384	6	-0.9	3.4
4	4	275	-272	-0.4	-3.2
5	0	-229	0	2.5	0.0
5	1	354	17	1.1	1.4
5	2	241	120	2.5	0.5
5	3	-28	-129	0.4	-3.0
5	4	-144	-110	3.1	-1.9
5	5	-53	71	4.5	-0.3
6	0	46	0	-1.6	0.0
6	1	59	-5	-1.3	1.7
6	2	7	109	-0.3	1.5
6	3	-244	68	0.9	1.5
6	4	-6	-35	-0.5	-0.6
6	5	-1	-14	-2.1	-0.5
6	6	-92	-17	1.5	-0.9
7	0	76	0	1.1	0.0
7	1	-52	-57	-0.0	-1.1
7	2	-2	-25	-1.0	-0.9
7	3	19	-15	-1.1	0.5
7	4	-32	5	-1.1	-1.0
7	5	-19	20	-1.5	-0.5
7	6	10	-24	1.0	1.5
7	7	-7	-22	-2.3	0.9
8	0	14	0	-0.4	0.0
8	1	7	9	0.6	0.2
8	2	-5	-6	0.3	0.8
8	3	-16	18	-0.2	-0.5
8	4	-2	-22	-0.6	-0.0
8	5	2	5	-0.7	-1.1
8	6	-3	16	-0.5	-1.5
8	7	2	-7	-1.9	-1.9
8	8	0	-25	-0.7	-3.4

TABLE 1(f)

EPOCH = 1965.0 USCGS(5/66&3/68)

N	M	G	H	GT	HT
1	0	-30388	0	15.0	0.0
1	1	-2117	5760	10.5	-4.0
2	0	-1637	0	-21.1	0.0
2	1	2981	-2004	2.7	-7.1
2	2	1583	127	0.5	-17.8
3	0	1153	0	1.3	0.0
3	1	-1989	-425	-14.1	1.1
3	2	1282	243	0.9	-3.0
3	3	855	-161	-2.5	-6.2
4	0	925	0	-4.8	0.0
4	1	806	148	-0.8	0.9
4	2	489	-293	-6.6	7.3
4	3	-382	11	-1.8	4.6
4	4	256	-249	-1.8	-5.0
5	0	-203	0	2.6	0.0
5	1	348	10	4.0	4.9
5	2	242	135	3.8	1.4
5	3	-31	-122	3.8	-4.3
5	4	-158	-95	0.8	4.2
5	5	-66	76	-0.8	-1.4
6	0	58	0	1.7	0.0
6	1	71	-16	-1.6	-1.9
6	2	1	108	2.3	-3.3
6	3	-232	55	2.3	2.8
6	4	-3	-23	-3.8	-3.2
6	5	1	-13	0.5	-0.6
6	6	-108	-13	-0.8	3.2
7	0	76	0	-2.1	0.0
7	1	-33	-36	-0.9	-3.8
7	2	4	-14	-0.9	2.2
7	3	14	-10	-2.4	0.6
7	4	-25	8	1.8	0.6
7	5	-14	25	1.4	2.8
7	6	20	-24	-1.5	-1.2
7	7	6	-18	-0.1	-0.9
8	0	3	0	0.4	0.0
8	1	12	-11	1.2	1.4
8	2	-3	-6	0.9	-0.4
8	3	-21	-3	1.1	-0.7
8	4	0	-15	0.2	0.3
8	5	3	2	-0.1	-1.3
8	6	-8	20	1.4	-1.9
8	7	14	0	0.3	0.2
8	8	8	-16	-1.1	-0.2

TABLE 1(g)

EPOCH = 1965.0 RCO(3/68)-1(LEATON,BASED ON LME)

N	M	G	H	GT	HT
1	0	-30372	0	15.5	0.0
1	1	-2083	5781	8.3	0.6
2	0	-1635	0	-26.6	0.0
2	1	2949	-1993	-1.3	-11.4
2	2	1582	108	1.3	-18.2
3	0	1161	0	0.0	0.0
3	1	-2025	-405	-9.5	3.2
3	2	1291	238	-1.9	1.5
3	3	872	-148	-0.6	-0.5
4	0	930	0	0.6	0.0
4	1	809	153	1.0	3.0
4	2	489	-274	-2.2	-0.7
4	3	-395	8	0.2	2.7
4	4	262	-257	-3.0	-2.7
5	0	-179	0	0.8	0.0
5	1	360	21	0.4	1.9
5	2	249	135	1.5	2.3
5	3	-13	-121	-0.3	-1.8
5	4	-174	-100	-1.1	1.4
5	5	-63	74	1.7	0.5
6	0	39	0	0.0	0.0
6	1	56	-18	-0.5	-2.2
6	2	11	102	1.8	0.2
6	3	-244	59	1.4	0.9
6	4	21	-38	0.6	-2.1
6	5	8	-21	0.2	-0.1
6	6	-116	-9	-2.2	-0.2
7	0	81	0	0.0	0.0
7	1	-54	-48	0.0	0.0
7	2	7	-32	0.0	0.0
7	3	10	-14	0.0	0.0
7	4	-36	6	0.0	0.0
7	5	-15	24	0.0	0.0
7	6	11	-21	0.0	0.0
7	7	4	-24	0.0	0.0
8	0	8	0	0.0	0.0
8	1	18	2	0.0	0.0
8	2	-8	-5	0.0	0.0
8	3	-20	7	0.0	0.0
8	4	6	-18	0.0	0.0
8	5	19	9	0.0	0.0
8	6	-3	27	0.0	0.0
8	7	10	10	0.0	0.0
8	8	4	-14	0.0	0.0

TABLE 1(h)

Table	Field Model	Reference
1a	GSFC(12/66)	Cain et al., 1967
1g	USC&GS	Hurwitz et al., 1966
1h	RGO-1(LME)	Leaton et al., 1965

Test Data

Although no explicit formula was agreed upon prior to the meeting for the derivation of an IGRF, there was an understanding that the considerations would need to be somehow based on the correspondence between the field components predicted by the proposed models and the available survey data.

Since the epoch of this IGRF was to be 1965, an arbitrary data cutoff time of 1961 was chosen so the results would not be too heavily weighted by observations prior to 1965. Testing was done on all data available since that date. These were divided into the major categories as follows:

a) surface magnetic observatory annual means 1961-1967

b) surface magnetic surveys. This category includes land surveys, repeat stations, shipboard and ship-towed observations.

c) aeromagnetic survey of Japan (1965) [Nagata, 1966]

d) aeromagnetic survey of Canada (1961-1963)

e) aeromagnetic survey of Scandinavia (1965)

f) project MAGNET worldwide (principally oceanic) airborne survey (1961-1966) [USNOO, 1965]

g) OGO-2 data as available during magnetically quiet intervals October, 1965 - September, 1967

h) OGO-4 data during magnetically quiet intervals July - December, 1967

i) 1964-83c observations - 1964-1965 [Zmuda et al., 1968]

j) COSMOS-49 observations - 1964.8

k) Other airborne (towed proton magnetometer data)

All of the non-satellite data were obtained from the file prepared by the Geomagnetic Division of the U.S. Coast and Geodetic Survey (E.Fabiano and S.Cain, WMS Volume, 1969). This file contained the contributions from many separate organizations and survey groups and is constantly updated as new observations are submitted. This file was edited by rejecting those observations deviating from the GSFC(12/66) model (using $n^* = 10$) by more than 1000γ. This procedure was used to eliminate the highly anomalous data beyond about five times the rms (root-mean-square) deviation. Since all models were truncated to $n^* = 8$ for testing, it gave no particular advantage to GSFC(12/66). This model was used since it fitted the data set best, hence eliminating the smallest fraction of data. The amount rejected is seen to be small as given in Table 2:

TABLE 2

NON-SATELLITE DATA ELIMINATED FOR $\Delta C > 1000\gamma$

	Data Type	Component Observations*	Data Rejected No.	Data Rejected %
a)	Observatory	1984	34	1.7
b)	Surface	22425	204	.9
c)	Japanese Air	1461	6	.4
d)	Canadian Air	9470	27	.3
e)	Scandinavian Air	6973	1	.01
f)	Project MAGNET	104228	401	.4
k)	Other Air	1763	9	.5

* In this and ensuing discussion a válue of D, I, H, Z, or F is counted as one observation even though other values may have been measured at the same time and location.

The OGO-2 and OGO-4 data (sampled every 30 seconds or at a spacing of approximately 200 km) were initially selected from periods of time for which Kp = 0. They were then fit with a special model listed in Table 3 [POGO(10/68)] employing 143 internal coefficients and their first time derivatives. The distribution of deviations of the data from this fit was as follows:

$\lvert\Delta F\rvert\gamma$	0	10	20	30	40	50	60	70	100	200	600	Total
Obs.	27646	4218	589	141	23	26	6	2	9	4		32664

Since the distribution indicated that the 15 observations over 70γ were likely anomalous, they were rejected and the resulting rms deviation computed to be 7γ. The remaining 32649 observations were included in the testing.

The COSMOS-49 data were similarly treated by fitting with a special function and eliminating those data that deviated significantly from the rest. The data were prepared by the U. S. Coast and Geodetic Survey from the catalog published by IZMIRAN (Dolginov et al., 1967). These were sorted into time order and each fourth observation fit with a series of 99 spherical harmonic coefficients. Data exceeding 100γ from the fitting surface were rejected in the coefficient determination. The distribution of residuals from this model, labelled COSMOS(9/68), is as follows:

$\lvert\Delta F\rvert\gamma$	0	10	20	30	40	50	60	70	80	90	100	Total
Obs.	1853	1243	648	271	93	41	23	18	19	15	138	4362

The use of every fourth observation in the fit is adequate for these purposes since each orbit then contains about 10 observations for the shortest wavelength used of the fitting function ($n^* = 9$ corresponds to $360/9 = 40^{\circ}$). Since the RMS deviation of these data from the COSMOS(9/68) field was 21γ, the selection used for model testing were those deviating less than 60γ, a total of 16554 from the approximately 18,000 originally available.

The 1964-83c observations entered the testing unedited except for the rejection of one spurious point that gave a $\lvert\Delta F\rvert > 1000\gamma$.

Test Results

The various models were tested against the data sets both with the limitation of 80 coefficients and also using all coefficients if more were available. Table 3 illustrates for the GSFC(12/66) model the distribution of residuals using the first 80 coefficients as well as the full number. Since the surface data were edited with this model using a 1000γ criteria, there can be no residuals above this figure with 120 coefficients. The effect of the truncation is seen to increase the rms residuals by 10-20γ regardless of their magnitude. Using 80 terms has only a small percentage effect on the surface data since magnetic anomalies account for a great deal of the scatter. The consequence on the satellite data is more obvious as seen in the OGO-2 results. Here the effect is to increase the observations in the 50-100γ range from 5 to 10% of the total data, and to push the number over 100γ from 1 to 3%.

These distributions were also calculated for each of the other test models and the rms values compiled in Table 4. Here the relative match of each data set to each model can be readily compared.

Although for each model there is an improvement with an increase in coefficients, the differences are generally smaller for those with higher average residuals.

TABLE 3

Distribution of Residuals from GSFC(12/66) Using n* = 8 (80 coeffs) and n* = 10 (120 coeffs)

TYPE	COEFFICIENTS	RESIDUAL RANGE (γ) 0	50	100	250	500	1000	TOTAL OBSERVATIONS	RMS (γ)
Observatory	120	740	414	532	205	59	0	1950	187
	80	490	499	653	227	81	0		198
Land/Sea	120	7089	5418	7071	2081	562	0	22221	180
	80	5202	4686	8778	2876	660	19		202
Japanese Air	120	362	301	491	252	49	0	1455	211
	80	331	274	504	294	51	1		226
Canadian Air	120	2112	1935	3633	1516	247	0	9443	202
	80	1865	1683	3593	1974	328	0		225
Scandinavian Air	120	2113	1718	2573	537	31	0	6972	145
	80	1715	1560	2889	776	32	0		163
Project MAGNET	120	28130	23357	37245	13003	2101	0	103827	186
	80	23967	21834	39609	15987	2397	33		200
COSMOS-49	120	15446	1095	13	0	0	0	16554	27
	80	11557	4463	534	0	0	0		48
1964-83c	120	1242	75	13	0	0	0	1330	28
	80	1206	112	12	0	0	0		32
OGO-2	120	18296	948	249	0	0	0	19493	27
	80	16878	2022	592	1	0	0		39
OGO-4	120	9300	3037	819	0	0	0	13156	51
	80	8448	3363	1341	2	0	0		61

TABLE 4

Root-Mean-Square Deviations of Test Data From Various Models
Using n* = 8 and n* = Maximum Degree and Order of Expansions

	DATA	n*	GSFC 12/66	POGO 3/68	POGO 10/68	AFCRL 11/67	3/68	RGO LME[1]	Malin[2]	IZMIRAN	USC&GS	IGRF 10/68
Observatory	1950	8	198	211	203	208	208	223	202	272	245	196
		max	187	204	193	201	197			271	236	
Land/Sea	22221	8	202	203	207	214	204	290	253	258	331	201
		max	180	186	187	209	192			248	323	
Japanese	1455	8	226	234	239	223	243	249	255	259	276	227
		max	211	215	220	216	221			244	233	
Canadian	9443	8	225	227	226	240	238	230	223	234	249	223
		max	203	209	205	212	221			237	236	
Scandinavian	6972	8	162	159	159	163	178	185	162	255	197	167
		max	145	138	140	150	164			253	190	
Project MAGNET	103827	8	200	232	215	216	209	234	216	330	244	201
		max	186	221	202	217	204			325	237	
COSMOS-49	16554	8	48	49	51	80	67	149	99	47	146	50
		max	27	30	21	77	61			19	139	
1964-83c	1330	8	32	34	33	68	47	85	58	33	96	32
		max	28	31	29	67	45			31	93	
OGO-2	19493	8	39	28	30	52	57	98	66	94	110	39
		max	28	11	7	47	49			94	108	
OGO-4	13156	8	61	39	40	85	89	126	89	114	144	57
		max	51	15	9	82	80			114	142	
Max. value of n*			10	9	11	10	10	8	8	9	12	8

Weighting of IGRF

It was decided that a weighted average of coefficients would provide the best compromise to an IGRF. With the restriction that models to be included should be based on truly spherical coefficients, the RGO(LME) and USCGS models were eliminated for inclusion in the main field averaging. Since the surface data residuals were so greatly influenced by crustal anomalies, it was decided to base the weights on the residuals to the satellite data.

Several different weighting schemes were tried. Generally, the exact weights used did not alter the overall results appreciably as long as those models fitting the satellite data best had an advantage. The POGO(3/68) and AFCRL(11/67) models were eliminated from the considerations since there was another model submitted by the same organization.

After several semi-qualitative arguments and considerations that the IGRF should be most useful near 1965.0, the following table of relatively weights were agreed upon to be applied as inverse square factors in combining the main field terms:

Model	σ
GSFC(12/66)	40
AFCRL(3/68)	70
RGO(3/68)-2	80
IZMIRAN(3/68)	100

The GSFC model was given the 40γ weight even though it had a 61γ residual to the OGO-4 data since the OGO-2 figure was 39γ, the other satellite residuals were low, and it has the overall lowest residuals to the surface data. The AFCRL model and RGO contributions were roughly equivalent but the AFCRL was given a slightly smaller figure due to its lower residual to OGO-2, COSMOS-49 and the surface data. The IZMIRAN model was assigned a slightly higher weight because of its uncertainty in the polar regions due to its being derived from data at less than 50° latitude. This possible difficulty is evidenced by its relatively high residuals to data sets containing polar contributions (e.g., OGO-2, OGO-4, observatory, land/sea, Scandinavian airborne, and Project MAGNET).

There was less basis for rational comparisons in combining the secular change terms. Hence each model previously used was weighted equally and the USCGS and RGO-1 models included since the secular change was independently derived for each.

Although more lengthy considerations may have resulted in an improved procedure for deriving the first IGRF, this formulation provided a model composed of some contribution from each organization and at the same time, within the restrictions as to the number of coefficients, produced a model which agrees tolerably well with the test data set. This agreement is seen in the last column of Table 4. Surprisingly, the procedure appeared to produce a residual equal to <u>or less</u> than that of the contributing models for some of the data sets at the $n^* = 8$ truncation level.

The Resulting Model IGRF(10/68)

Since the IGRF is a composite of several models, it can be compared with each as given in Table 5. Here is listed for each of the contributing coefficient sets the deviation from the resulting IGRF. Although the disagreements between the various terms are sometimes relatively large for those with amplitudes of the order of 1 to 10γ, those of higher magnitude are surprisingly close. Of the main field terms there seems to be the largest discrepancy between those having $m = 1$, particularly for the IZMIRAN model with $n = 1, 2, 3, 4$, and 6.

The final IGRF(10/68) coefficients are given in Table 6 and maps of the field and its secular change given in Appendix 1. Appendix 2 gives a possible minor modification based on a suggested change of scale to a standard mean earth radius of 6371 in place of 6371.2 km.

Recommendations

We would like to make a few recommendations as to the way an international reference field might be used. As can be seen in this report and others we have published (Cain et al., 1965; Cain et al., 1967; Cain and Hendricks, 1968), ambient values of the earth's field are dependent on contributions from the core, crust, subsurface, and ionospheric electric currents, and the effects of trapped plasma, magnetospheric boundary, and tail effects. The exact secular variation is subject to shifts which make a linear fit with time increasingly uncertain beyond a few years. Further, even for the decade of validity of the IGRF, 1960-1969, we already know that there are more accurate models available.

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n	m	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	6	0	-11	-20	0	6	-30339
1	1	5	-10	8	-25	11	-15	-2123
2	0	-6	-3	14	24	-7	-3	-1654
2	1	3	-1	-15	6	5	-2	2994
2	2	-6	12	18	-15	28	6	1567
3	0	3	5	-18	1	5	10	1297
3	1	-6	-3	28	2	-6	1	-2036
3	2	0	1	0	0	10	5	1289
3	3	5	13	19	-85	14	24	843
4	0	-1	7	-18	18	-2	-4	958
4	1	2	1	-13	9	-2	7	805
4	2	2	2	-8	-7	-15	-1	492
4	3	-2	1	3	4	11	8	-392
4	4	-7	14	3	10	-1	20	256
5	0	-2	3	16	-19	0	-7	-223
5	1	2	-6	19	-13	3	-4	357
5	2	1	-7	-7	17	1	-4	246
5	3	-3	0	-2	21	-7	-2	-26
5	4	0	10	-5	-13	-7	17	-161
5	5	-1	7	-13	9	-3	-2	-51
6	0	0	-1	-8	15	-1	-1	47
6	1	2	-5	-5	8	1	-1	60
6	2	-1	2	-2	2	6	3	4
6	3	3	-8	-4	3	-4	-15	-229
6	4	0	-2	4	-1	0	-9	3
6	5	3	-8	7	-16	-7	3	-4
6	6	5	9	0	-48	-32	20	-112
7	0	-2	4	6	-7	1	5	71
7	1	-2	1	7	-1	1	2	-54
7	2	0	-3	2	4	4	-2	0
7	3	-1	8	0	-9	2	7	12
7	4	1	-2	-3	6	2	-7	-25
7	5	1	-2	-3	1	3	-11	-9
7	6	2	-7	2	0	-1	-3	13
7	7	3	-10	7	-8	-7	-5	-2
8	0	0	-1	-4	6	0	4	10
8	1	0	-4	4	1	-6	-2	9
8	2	3	-2	-3	-6	-2	-2	-3
8	3	2	-2	-5	2	2	-4	-12
8	4	0	-4	6	-2	-1	2	-4
8	5	-2	-3	3	11	7	-4	7
8	6	-1	-2	0	13	9	1	-5
8	7	0	-3	0	4	3	-10	12
8	8	-1	2	0	2	3	-6	6

TABLE 5(a)

n	m	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0	0	0	0	0	0	0
1	1	0	16	12	-52	11	32	5758
2	0	0	0	0	0	0	0	0
2	1	4	-11	6	-9	-6	4	-2006
2	2	-11	10	-15	71	-7	12	130
3	0	0	0	0	0	0	0	0
3	1	6	-6	-22	12	-3	-2	-403
3	2	-2	-3	-1	22	-3	7	242
3	3	10	-19	20	-53	16	-8	-170
4	0	0	0	0	0	0	0	0
4	1	1	-6	12	-10	4	-10	149
4	2	6	-6	0	-28	5	-8	-280
4	3	3	-7	3	-9	7	-2	8
4	4	-16	-4	11	90	35	-7	-265
5	0	0	0	0	0	0	0	0
5	1	-1	11	2	-22	4	1	16
5	2	1	3	8	-23	1	-5	125
5	3	-5	5	1	23	-4	-7	-123
5	4	1	-10	10	1	9	-3	-107
5	5	4	3	-2	-25	-2	-7	77
6	0	0	0	0	0	0	0	0
6	1	2	-2	-3	-4	3	9	-14
6	2	-1	-1	1	6	1	3	106
6	3	1	0	-10	8	0	0	68
6	4	2	6	1	-26	-12	-2	-32
6	5	-2	3	-6	15	13	-4	-10
6	6	3	-4	3	-17	-12	-4	-13
7	0	0	0	0	0	0	0	0
7	1	-2	5	11	-16	-6	0	-57
7	2	0	-3	2	0	1	2	-27
7	3	2	-2	-2	-6	-1	-8	-8
7	4	2	-5	-1	3	-2	-4	9
7	5	-1	-3	1	8	1	-3	23
7	6	-1	3	-3	3	0	-5	-19
7	7	0	1	-4	4	-2	-5	-17
8	0	0	0	0	0	0	0	0
8	1	-1	7	-7	1	7	6	3
8	2	0	-1	6	-9	0	7	-13
8	3	-1	7	-4	-3	2	13	5
8	4	-2	3	1	6	5	-4	-17
8	5	1	-2	1	-6	-5	1	4
8	6	0	-3	2	4	4	-7	22
8	7	0	-1	7	-7	-7	-4	-3
8	8	-3	3	1	8	6	-9	-16

TABLE 5(b)

n	m	GT GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	-1.5	-3.3	1.7	3.3	-0.3	0.2	15.3
1	1	0.7	-1.9	0.3	-1.0	1.8	-0.4	8.7
2	0	0.3	-3.3	0.4	-0.7	3.3	-2.2	-24.4
2	1	-0.5	-0.5	-1.3	-0.2	2.4	-1.6	0.3
2	2	-4.2	-2.0	3.6	0.4	2.1	2.9	-1.6
3	0	-1.7	0.1	-0.2	0.6	1.1	-0.2	0.2
3	1	0.0	0.6	0.8	1.9	-3.3	1.3	-10.8
3	2	1.7	0.5	-1.7	-0.7	0.2	-2.6	0.7
3	3	-3.1	-3.0	2.8	2.1	1.3	3.2	-3.8
4	0	2.1	1.4	-0.3	0.9	-4.1	1.3	-0.7
4	1	0.5	0.6	-0.2	0.1	-1.0	0.8	0.2
4	2	1.3	2.6	-1.0	0.7	-3.6	0.8	-3.0
4	3	0.8	-0.4	1.1	0.1	-1.7	0.3	-0.1
4	4	-1.4	1.2	-0.9	0.8	0.3	-0.9	-2.1
5	0	-0.0	1.4	-0.9	-1.3	0.7	-1.1	1.9
5	1	-0.5	-0.5	-1.1	-0.8	2.9	-0.7	1.1
5	2	0.9	-0.2	0.1	-1.8	0.9	-1.3	2.9
5	3	-0.6	-0.2	-1.6	-1.0	3.2	-0.9	0.6
5	4	-0.6	1.5	-1.0	-0.7	0.8	-1.1	0.0
5	5	0.8	2.7	-0.3	-1.2	-2.1	0.4	1.3
6	0	-0.4	-1.1	0.1	-0.4	1.8	0.1	-0.1
6	1	1.2	-0.7	0.3	0.6	-1.3	-0.2	-0.3
6	2	-0.2	-0.6	-0.1	-0.4	1.2	0.7	1.1
6	3	0.7	-0.7	0.1	-0.6	0.4	-0.5	1.9
6	4	1.2	0.9	0.4	0.8	-3.4	1.0	-0.4
6	5	0.6	-2.3	0.4	0.4	0.9	0.6	-0.4
6	6	0.6	0.6	-0.8	0.2	-0.6	-2.0	-0.2
7	0	-0.1	0.7	0.5	0.5	-1.6	0.5	-0.5
7	1	-0.0	-0.0	0.3	0.3	-0.6	0.3	-0.3
7	2	-0.9	-0.3	0.7	0.7	-0.2	0.7	-0.7
7	3	-0.4	1.3	0.5	0.5	-1.9	0.5	-0.5
7	4	-0.3	-0.8	-0.3	-0.3	1.5	-0.3	0.3
7	5	-0.7	-0.7	0.0	0.0	1.4	0.0	-0.0
7	6	0.0	0.9	0.2	0.2	-1.3	0.2	-0.2
7	7	-0.1	-1.6	0.6	0.6	0.5	0.6	-0.6
8	0	0.3	-0.3	-0.1	-0.1	0.3	-0.1	0.1
8	1	0.1	-0.1	-0.4	-0.4	0.8	-0.4	0.4
8	2	1.3	-0.5	-0.6	-0.6	0.3	-0.6	0.6
8	3	-0.2	-0.8	-0.0	-0.0	1.1	-0.0	0.0
8	4	0.5	-0.8	0.0	0.0	0.2	0.0	-0.0
8	5	-0.0	-0.1	0.1	0.1	-0.0	0.1	-0.1
8	6	0.2	-0.7	-0.3	-0.3	1.1	-0.3	0.3
8	7	0.1	-1.4	0.3	0.3	0.6	0.3	-0.3
8	8	0.0	-0.4	0.5	0.5	-0.6	0.5	-0.5

TABLE 5(c)

n	m	HT GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1	-1.7	1.4	2.3	-0.2	-1.7	2.9	-2.3
2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1	-2.3	-4.1	-0.2	2.0	4.7	0.4	-11.8
2	2	0.0	1.3	-1.3	0.9	-1.1	-1.5	-16.7
3	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	1.5	0.8	0.8	0.1	-3.1	-1.0	4.2
3	2	1.8	1.4	0.3	0.0	-3.7	0.9	0.7
3	3	1.1	-3.3	-1.3	2.1	1.5	-0.8	-7.7
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	-2.1	-1.4	1.1	1.5	1.0	3.1	-0.1
4	2	-1.4	-3.0	-0.6	-0.7	5.7	-2.3	1.6
4	3	-1.2	-0.2	0.1	-0.4	1.7	-0.2	2.9
4	4	-2.6	-0.3	1.2	2.6	-0.8	1.5	-4.2
5	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	-0.3	-0.1	-0.3	-1.9	2.6	-0.4	2.3
5	2	-0.1	0.5	0.3	-0.3	-0.3	0.6	1.7
5	3	-0.3	0.6	0.4	1.2	-1.9	0.6	-2.4
5	4	-0.3	-2.6	0.2	-0.6	3.4	0.6	0.8
5	5	0.1	0.2	0.3	0.5	-1.1	0.8	-0.3
6	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	1.1	0.5	-1.1	0.5	-1.0	-1.3	-0.9
6	2	0.4	0.5	1.4	0.6	-2.9	0.6	-0.4
6	3	0.6	-0.1	-0.0	-1.1	0.8	-1.1	2.0
6	4	-0.3	1.3	0.1	1.1	-2.1	-1.0	-1.1
6	5	0.4	0.5	-0.1	-0.1	-0.7	-0.2	0.1
6	6	-0.1	-1.3	0.1	-0.9	2.3	-1.1	0.9
7	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.1	0.5	1.1	1.1	-2.7	1.1	-1.1
7	2	-0.2	-1.1	-0.3	-0.3	1.9	-0.3	0.3
7	3	0.1	0.5	-0.4	-0.4	0.2	-0.4	0.4
7	4	0.6	-0.6	-0.2	-0.2	0.4	-0.2	0.2
7	5	-0.8	-0.8	-0.4	-0.4	2.4	-0.4	0.4
7	6	0.4	1.5	-0.2	-0.2	-1.4	-0.2	0.2
7	7	0.7	1.1	-0.3	-0.3	-1.2	-0.3	0.3
8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1	-0.7	-0.4	-0.1	-0.1	1.3	-0.1	0.1
8	2	-0.1	-0.0	0.2	0.2	-0.2	0.2	-0.2
8	3	0.4	-0.7	0.3	0.3	-0.4	0.3	-0.3
8	4	-0.7	-0.2	0.2	0.2	0.5	0.2	-0.2
8	5	0.4	-0.1	0.3	0.3	-1.0	0.3	-0.3
8	6	0.5	0.2	0.4	0.4	-1.5	0.4	-0.4
8	7	-0.1	-1.0	0.3	0.3	0.5	0.3	-0.3
8	8	-0.2	-0.4	0.3	0.3	0.1	0.3	-0.3

TABLE 5(d)

EPOCH = 1965.0 I.G.R.F.(10/68)

N	M	G	H	GT	HT
1	0	-30339	0	15.3	0.0
1	1	-2123	5758	8.7	-2.3
2	0	-1654	0	-24.4	0.0
2	1	2994	-2006	0.3	-11.8
2	2	1567	130	-1.6	-16.7
3	0	1297	0	0.2	0.0
3	1	-2036	-403	-10.8	4.2
3	2	1289	242	0.7	0.7
3	3	843	-176	-3.8	-7.7
4	0	958	0	-0.7	0.0
4	1	805	149	0.2	-0.1
4	2	492	-280	-3.0	1.6
4	3	-392	8	-0.1	2.9
4	4	256	-265	-2.1	-4.2
5	0	-223	0	1.9	0.0
5	1	357	16	1.1	2.3
5	2	246	125	2.9	1.7
5	3	-26	-123	0.6	-2.4
5	4	-161	-107	0.0	0.8
5	5	-51	77	1.3	-0.3
6	0	47	0	-0.1	0.0
6	1	60	-14	-0.3	-0.9
6	2	4	106	1.1	-0.4
6	3	-229	68	1.9	2.0
6	4	3	-32	-0.4	-1.1
6	5	-4	-10	-0.4	0.1
6	6	-112	-13	-0.2	0.9
7	0	71	0	-0.5	0.0
7	1	-54	-57	-0.3	-1.1
7	2	0	-27	-0.7	0.3
7	3	12	-8	-0.5	0.4
7	4	-25	9	0.3	0.2
7	5	-9	23	-0.0	0.4
7	6	13	-19	-0.2	0.2
7	7	-2	-17	-0.6	0.3
8	0	10	0	0.1	0.0
8	1	9	3	0.4	0.1
8	2	-3	-13	0.6	-0.2
8	3	-12	5	0.0	-0.3
8	4	-4	-17	-0.0	-0.2
8	5	7	4	-0.1	-0.3
8	6	-5	22	0.3	-0.4
8	7	12	-3	-0.3	-0.3
8	8	6	-16	-0.5	-0.3

TABLE 6

The IGRF was developed as a result of the request of those who would wish a standard field model where the permanence of a standard over a period of years outweighs the advantages of a high accuracy. Thus the ultimate use of this model and further requests for revisions must be left to the users.

The way to test whether IGRF(10/68) is suitable to any particular need is to periodically test newer or more accurate models and to decide on the basis of the differences whether the continued use is adequate. As the core field deviates more and more from the IGRF estimate, the accuracy will continuously decrease.

We have already made this test in regard to analysis of the time variations of the COSMOS-49, OGO-2, and OGO-4 data. For such studies the IGRF is quite useless, even the GSFC(12/66) model is insufficient, and fits based on the data themselves are being used. For higher accuracy studies, we would suggest using the GSFC(12/66) model over the range 1900-1965 and the POGO(10/68) model from 1965 through 1968. Beyond 1968, POGO(10/68) could be used until it is updated by more recent data and planned improvements in the analysis.

The computations of the magnetic field from the IGRF or other magnetic field coefficients can be effected using a wide variety of computer programs currently available. One such set of programs based on a code originally developed by Jensen and Whitaker (1960), may be obtained from:

World Data Center A for Rockets and Satellites
Goddard Space Flight Center (601)
Greenbelt, Maryland 20771

These codes convert the Schmidt normalized coefficients internally in the computer to a more efficient Gauss normalized form, update them to the epoch requested, and compute the geocentric components from the scalar gradient of the potential function given the geocentric position. Conversions are also provided so that one can enter the programs with a geodetic position which is then converted to geocentric, and also for rotating the output geocentric components into geodetic directions. Ignoring the differences between geodetic and geocentric coordinates will create errors up to about 200γ.

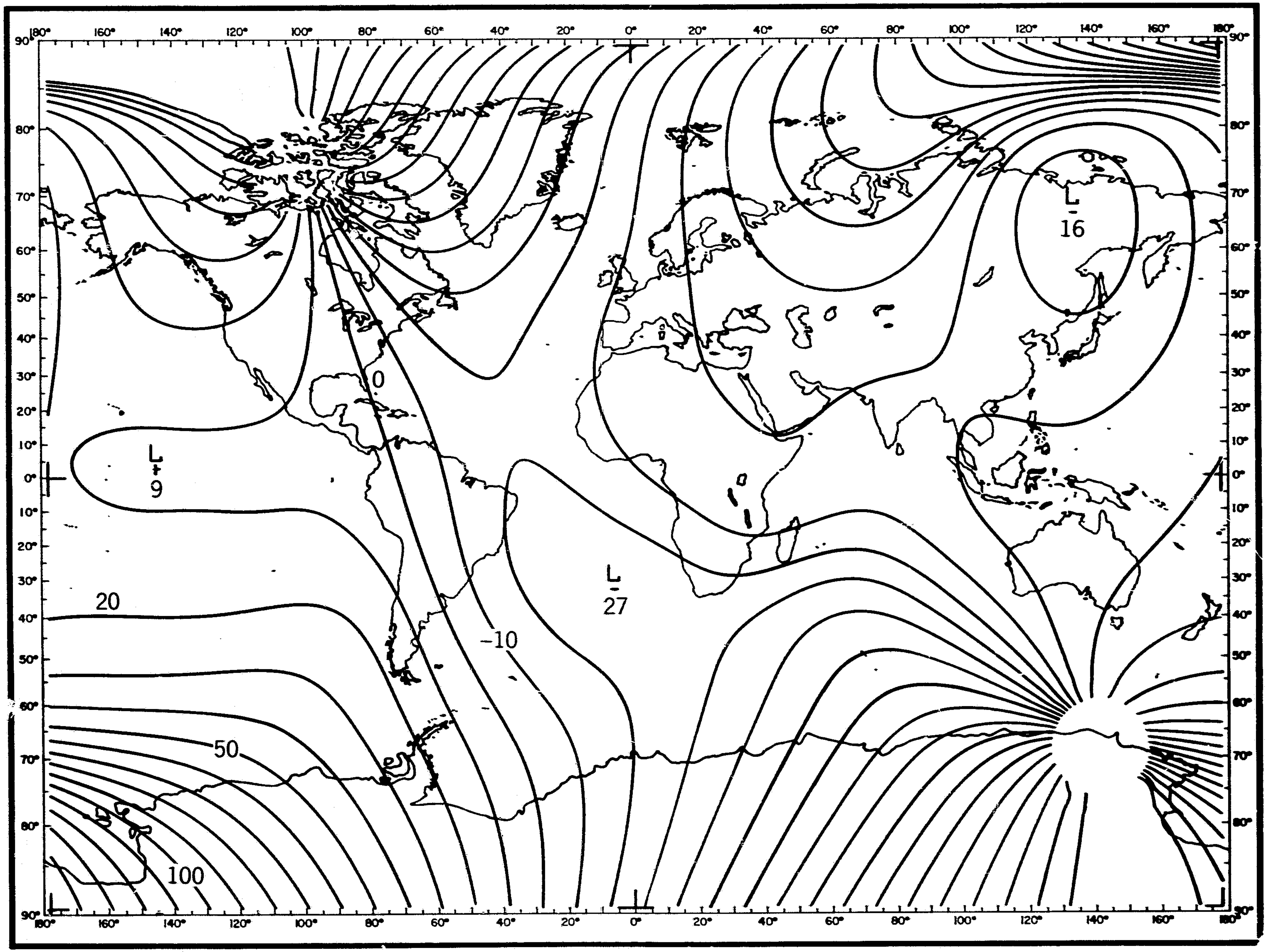
APPENDIX 1

Main Field Component and Isoporic Charts Computed From IGRF(10/68) for 1965.0 at the Earth's Surface

The following figures represent the surface contours of the various geodetic components of the geomagnetic field and its secular change as computed by the IGRF. These diagrams are very similar to those given by Cain and Hendricks (1968) for the GSFC(12/66) field and are drawn automatically using a computer program originally used for weather maps (Cain and Neilon, 1963).

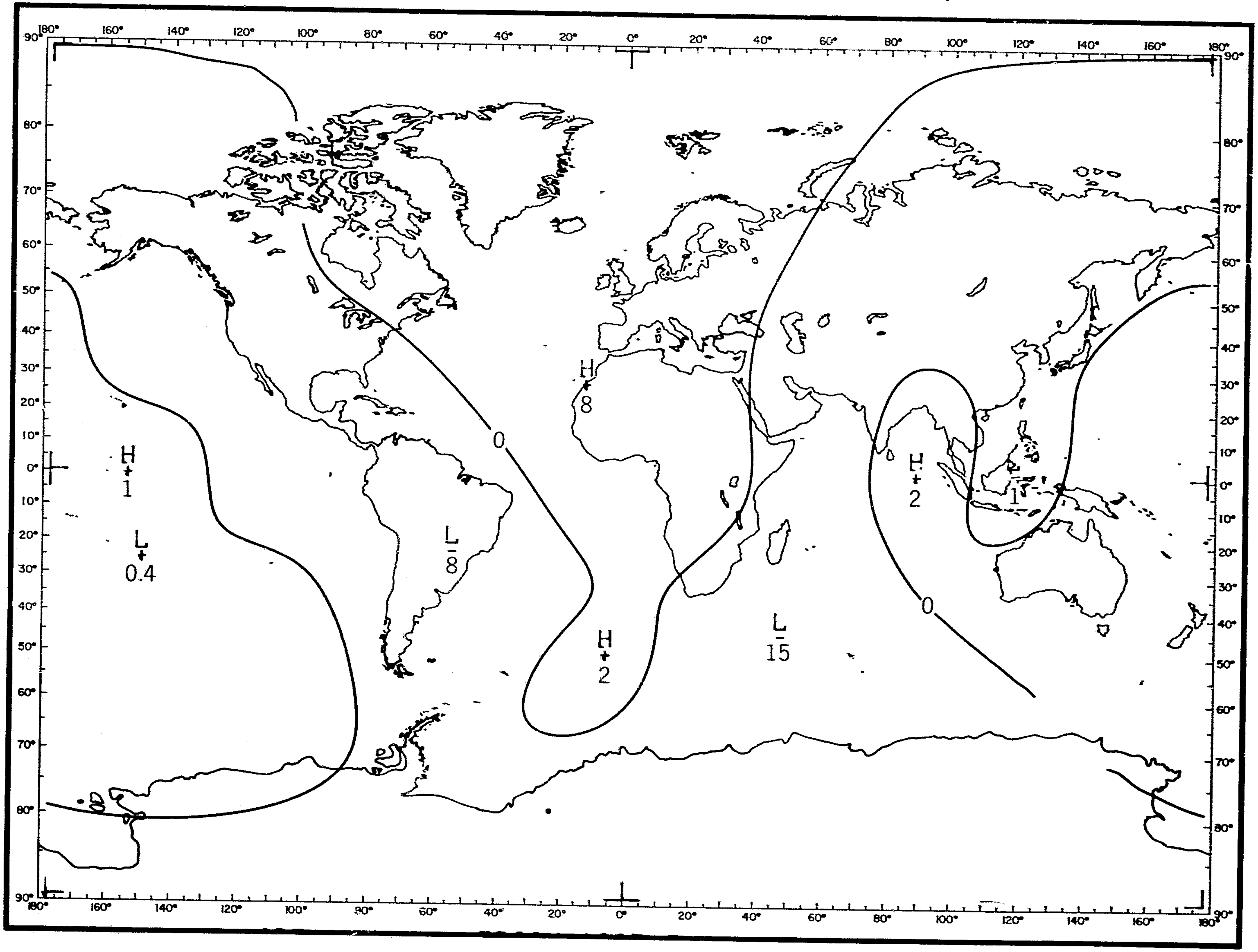
The plots thus are drawn including the algebraic "lows" and "highs" of the component being displayed. These extrema occur at the center of the "+" or "-" symbols. The dip poles are noted for the H chart as '⊕'.

DECLINATION (degrees) D



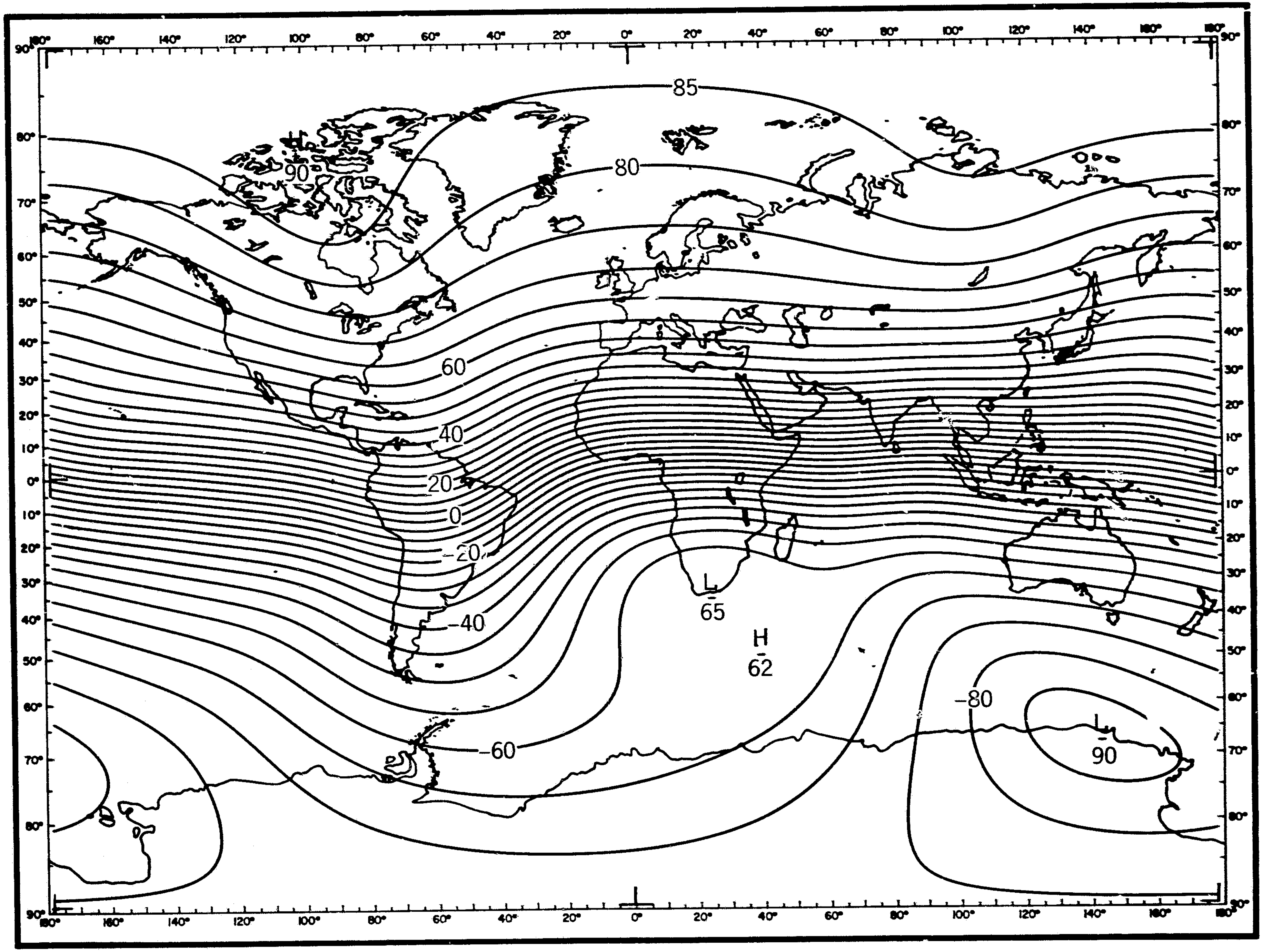
IGRF 1965

SECULAR CHANGES OF DECLINATION (minutes/year) $\dot{D}$



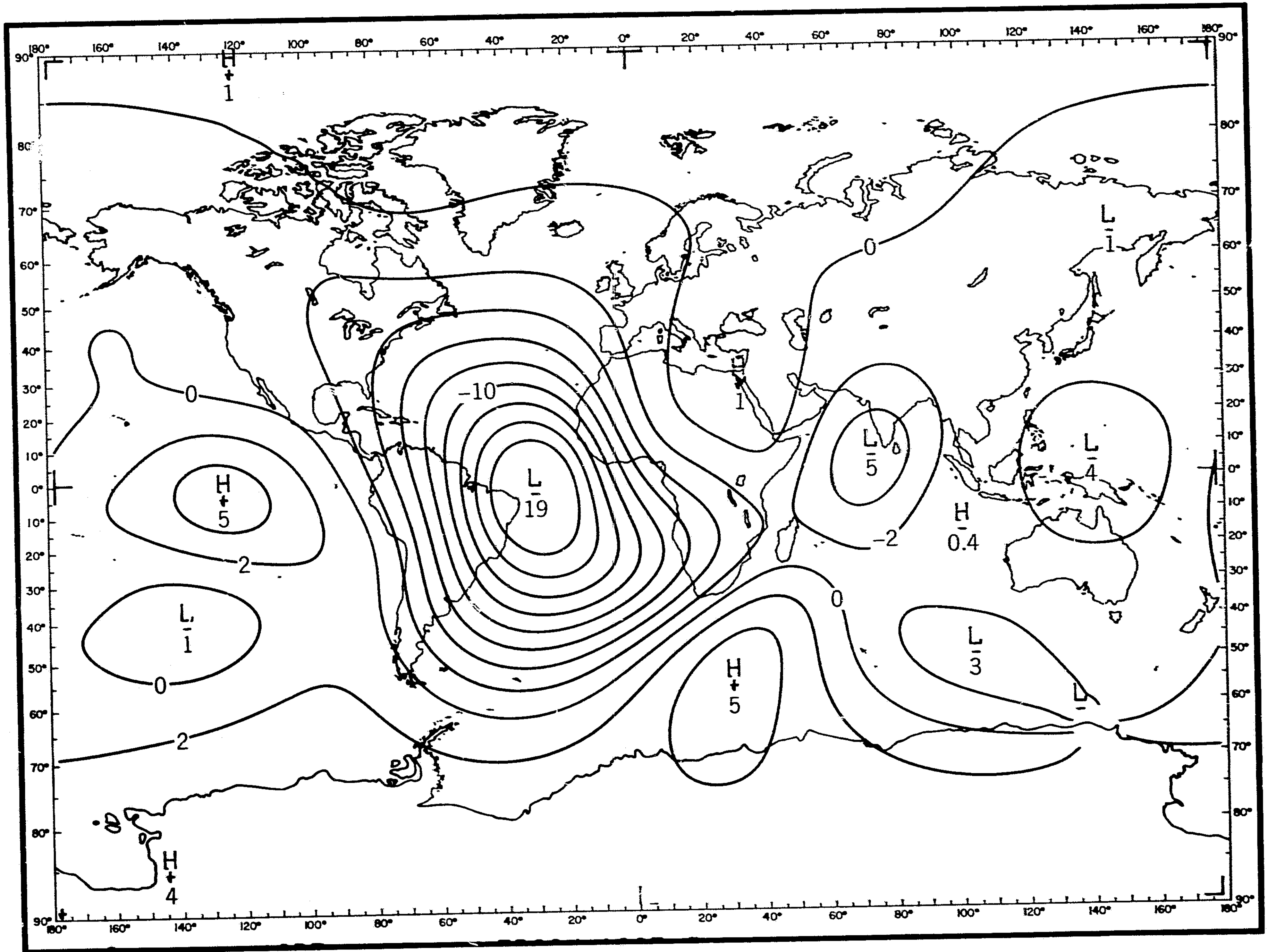
IGRF 1965

INCLINATION (degrees)



SECULAR CHANGES OF INCLINATION (minutes/year)

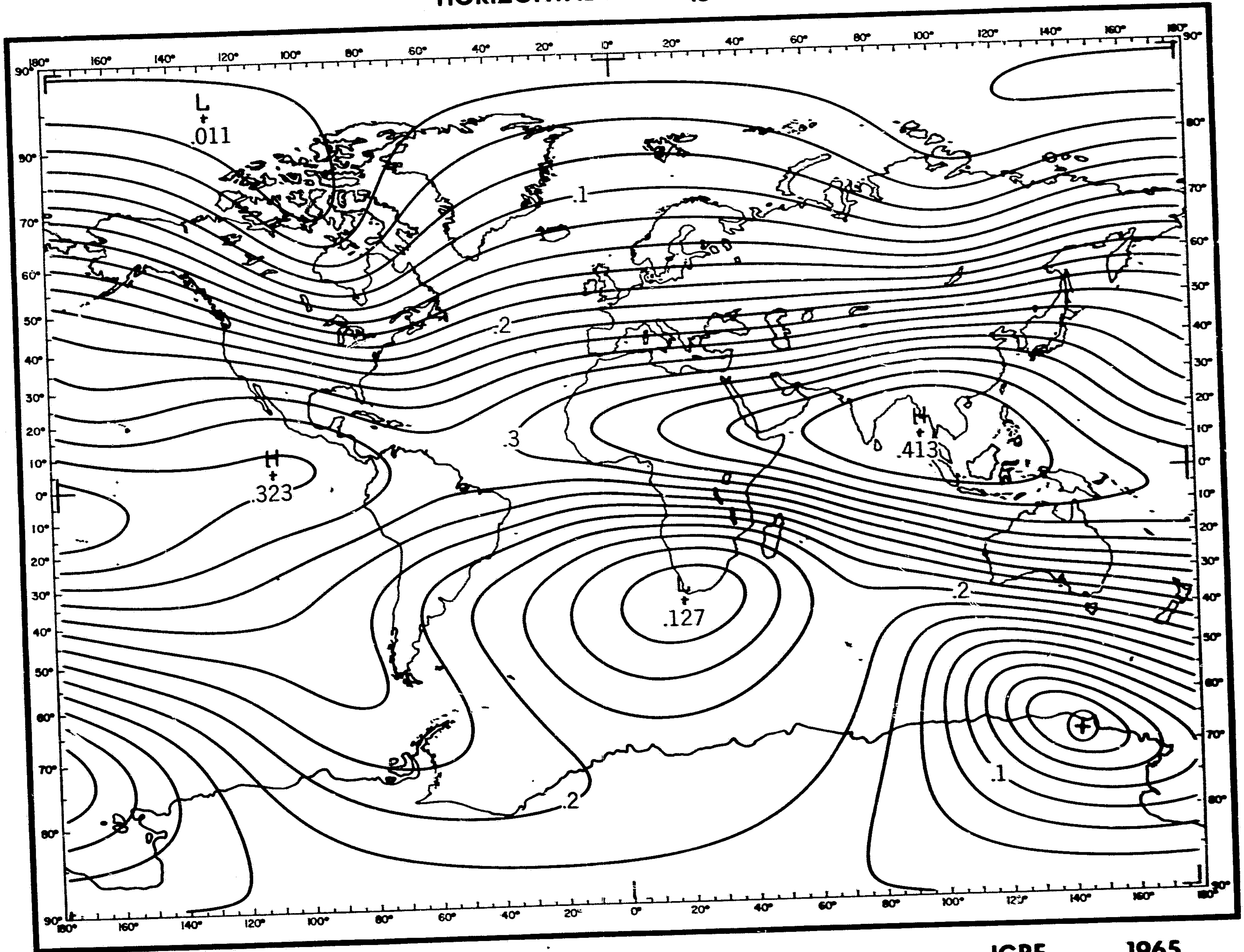
i



IGRF 1965

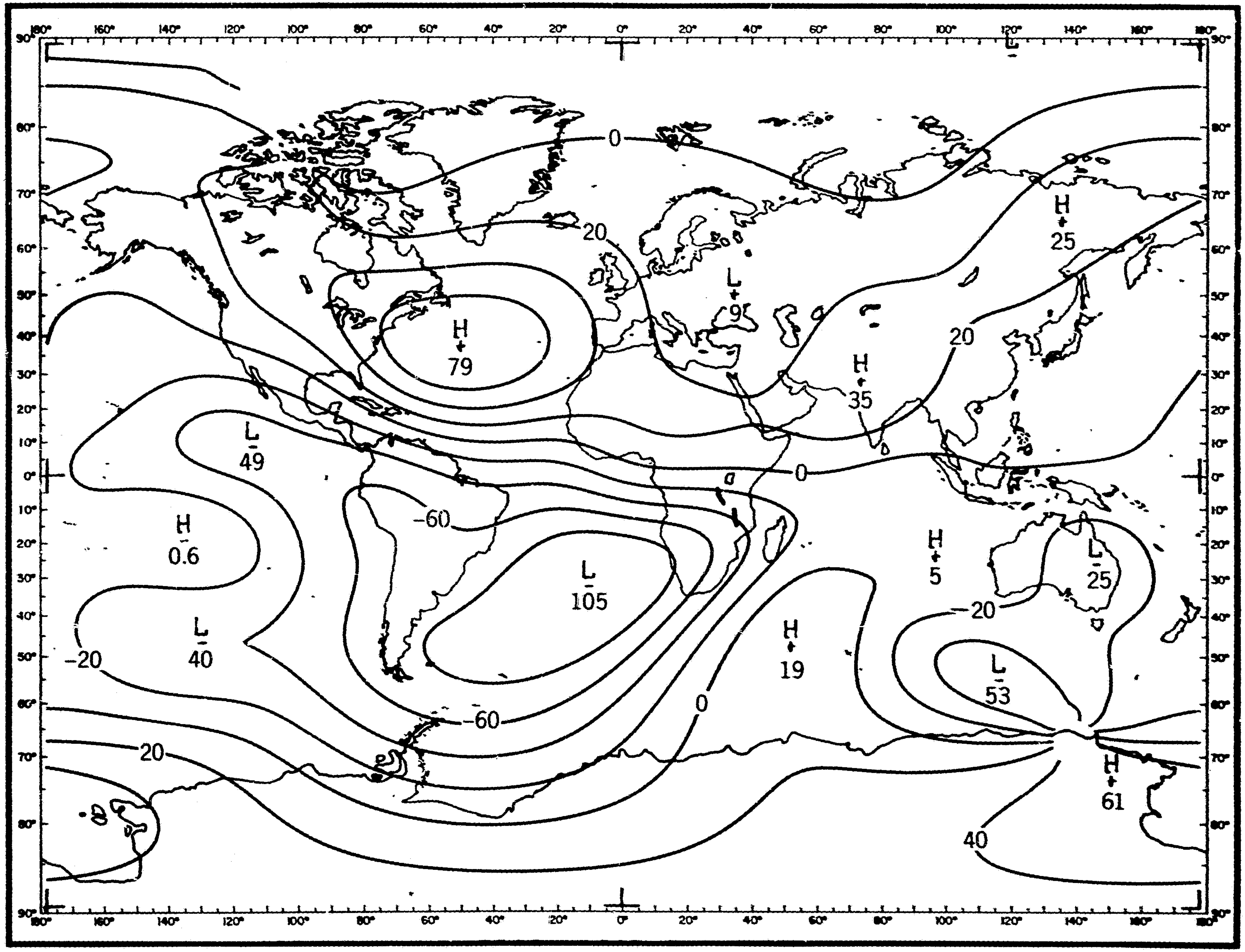
HORIZONTAL FORCE (gauss)

H



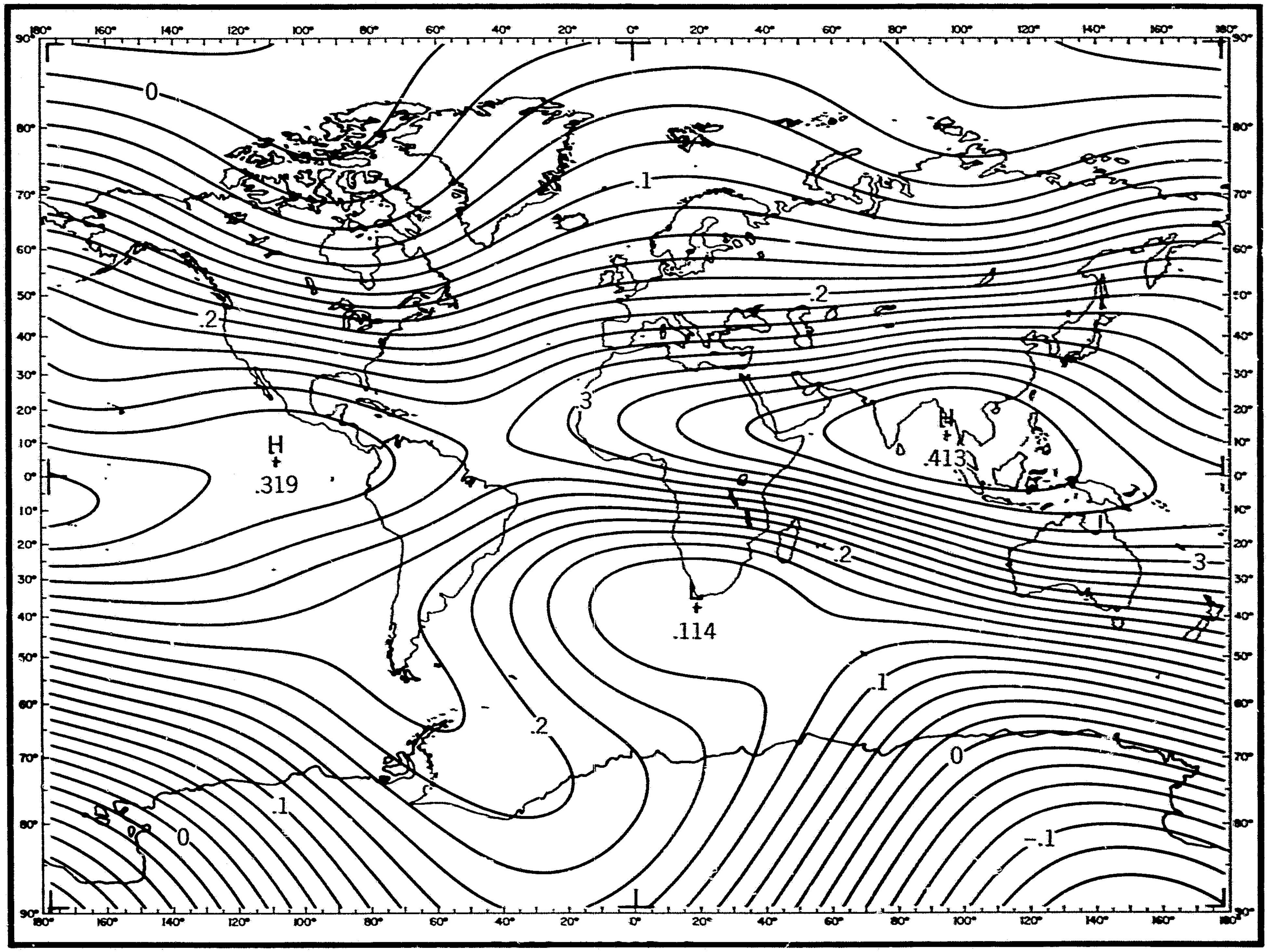
IGRF 1965

SECULAR CHANGE OF HORIZONTAL FORCE (gamma/year)



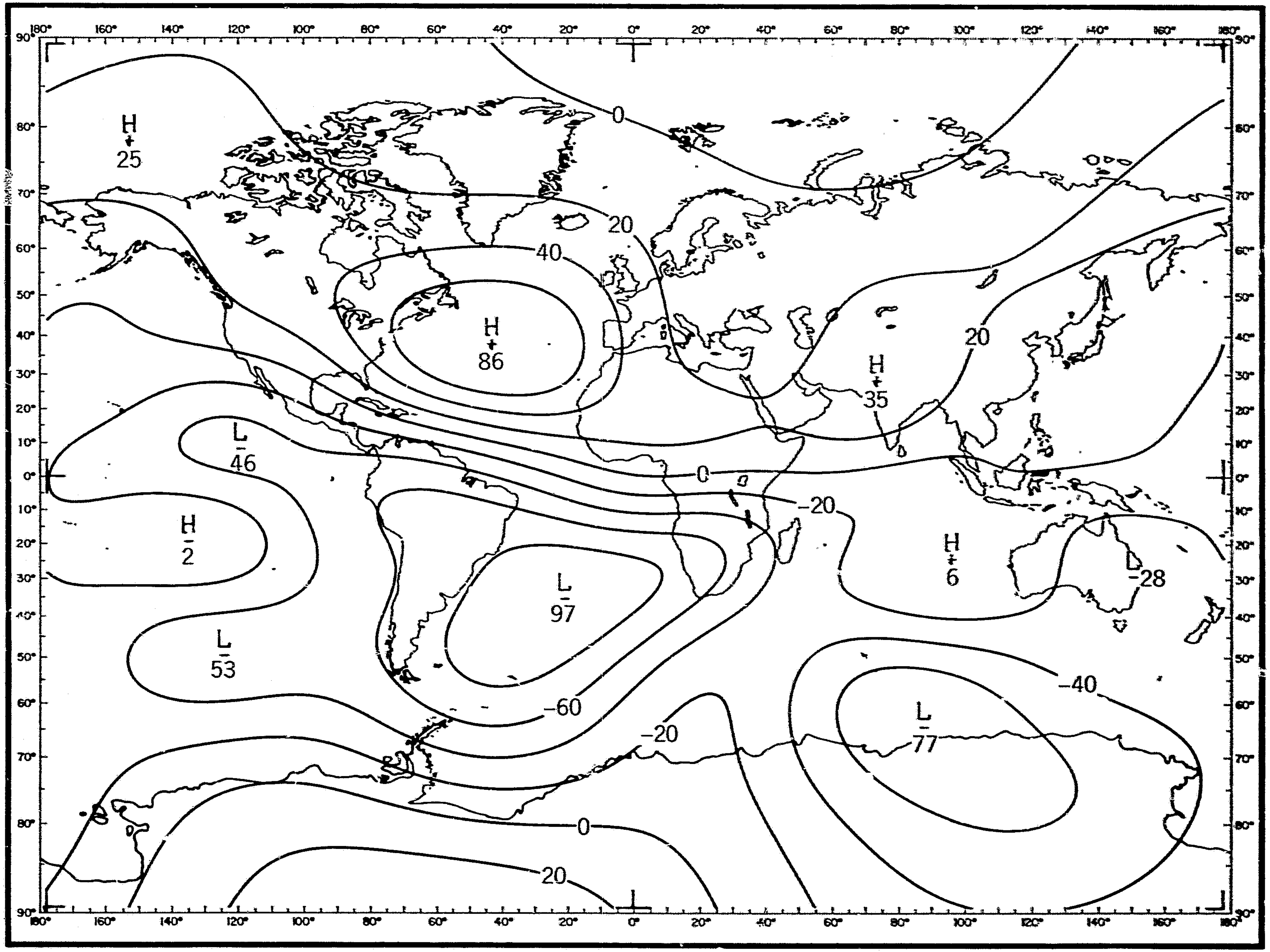
IGRF 1965

NORTH FORCE (gauss) X



IGRF 1965

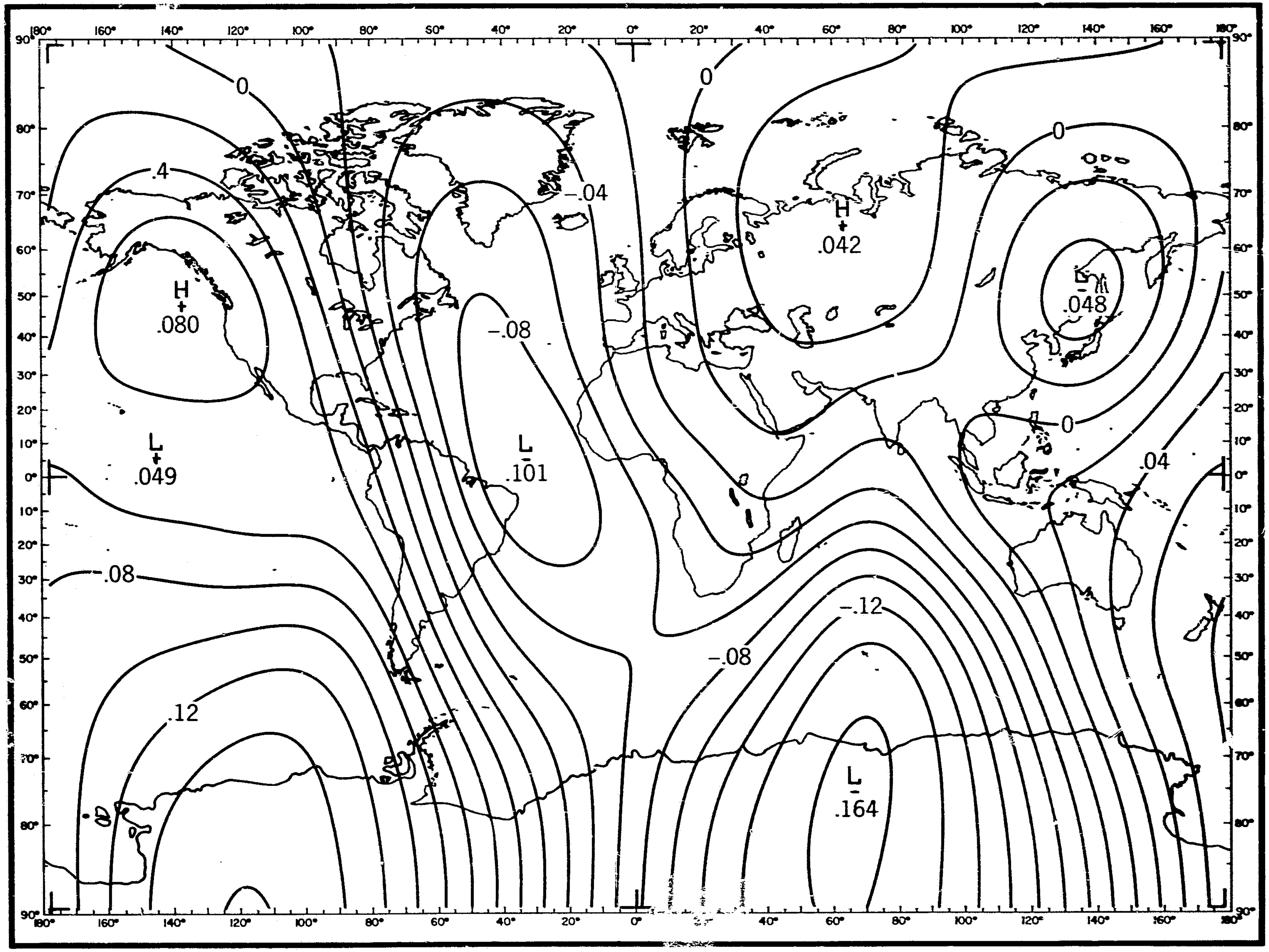
SECULAR CHANGE OF NORTH FORCE (gammas/year) $\dot{X}$



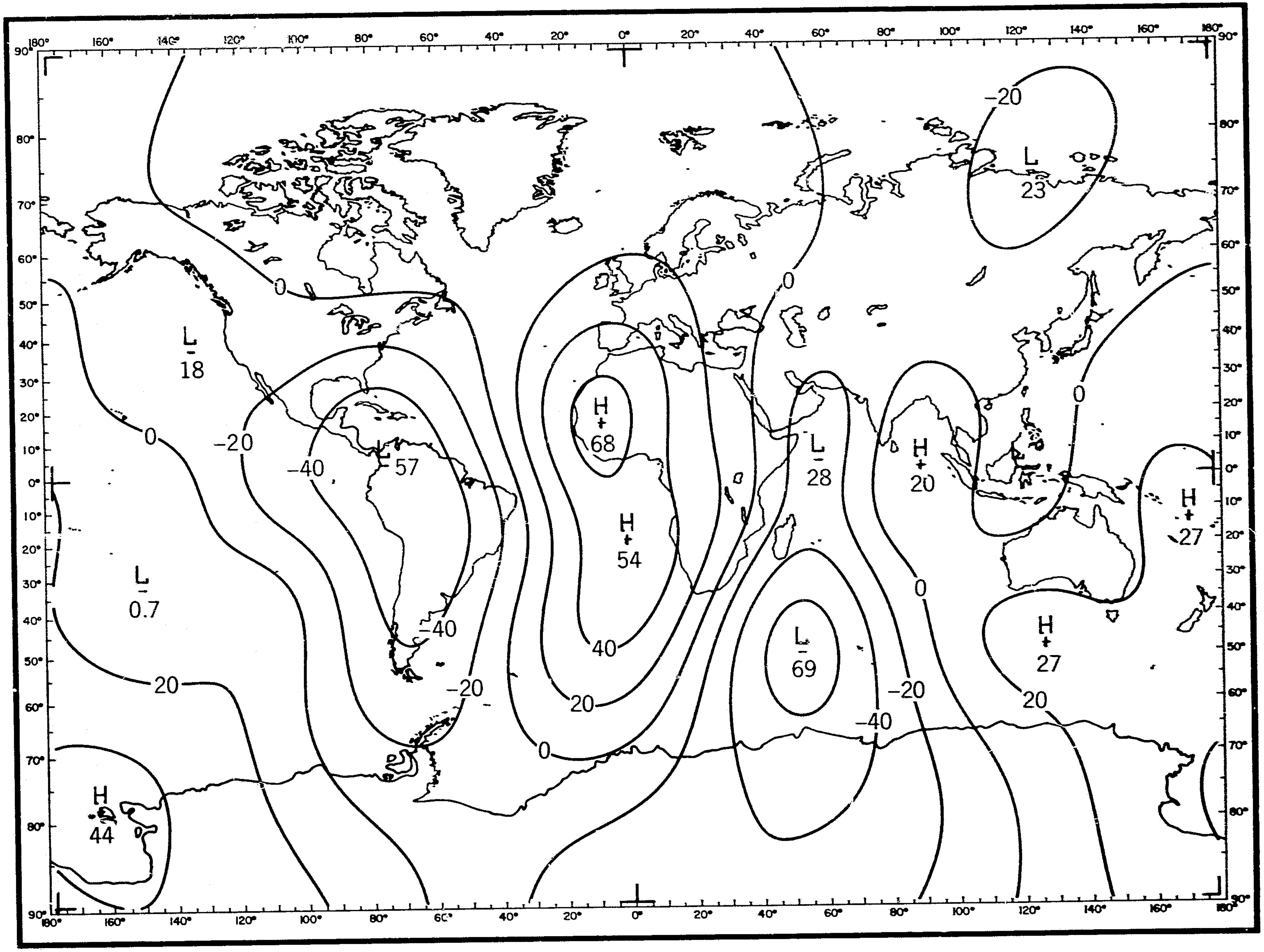
IGRF 1965

EAST FORCE (gauss)

Y

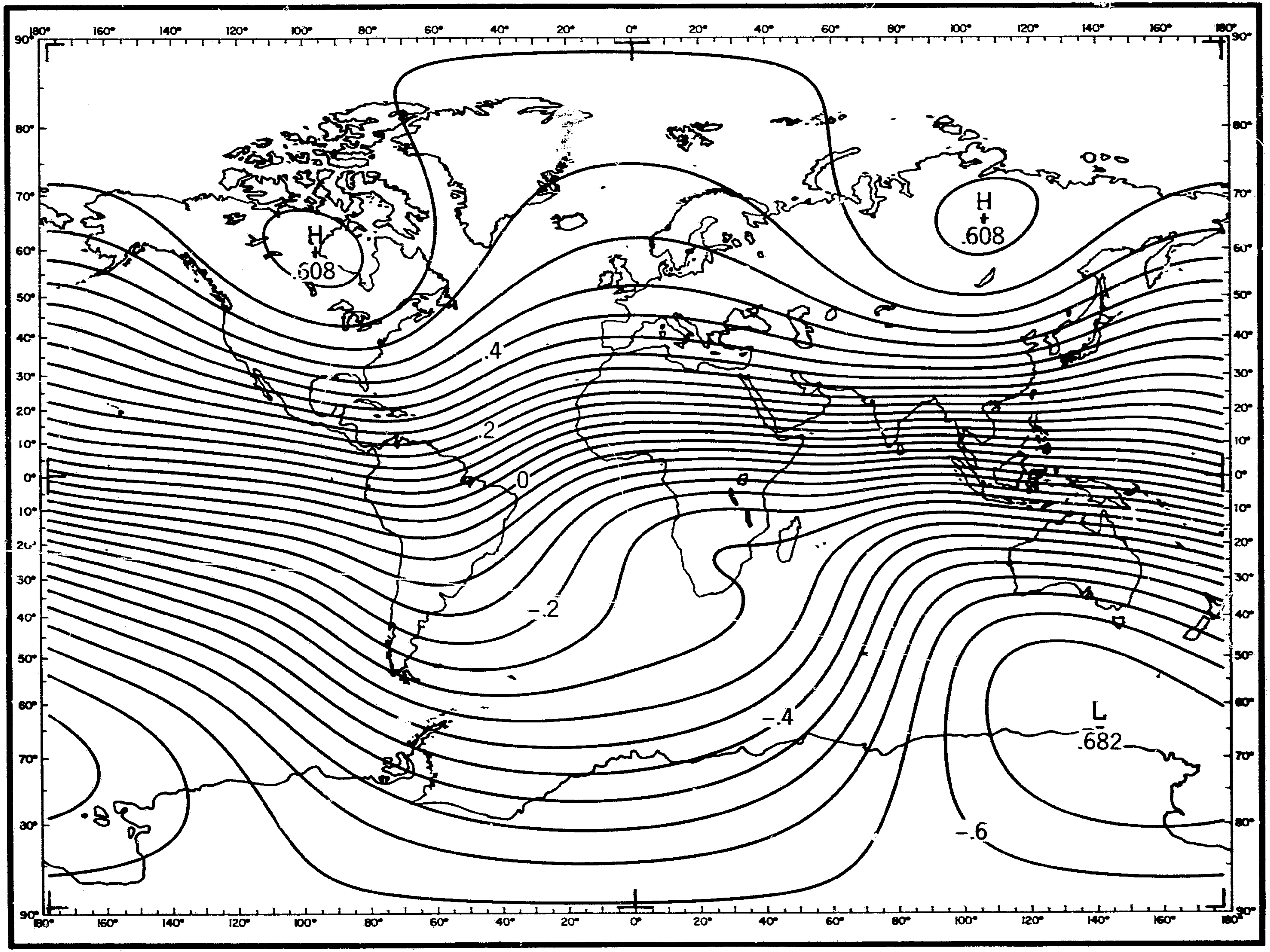


SECULAR CHANGE OF EAST FORCE (gammas/year) $\dot{Y}$



IGRF 1965

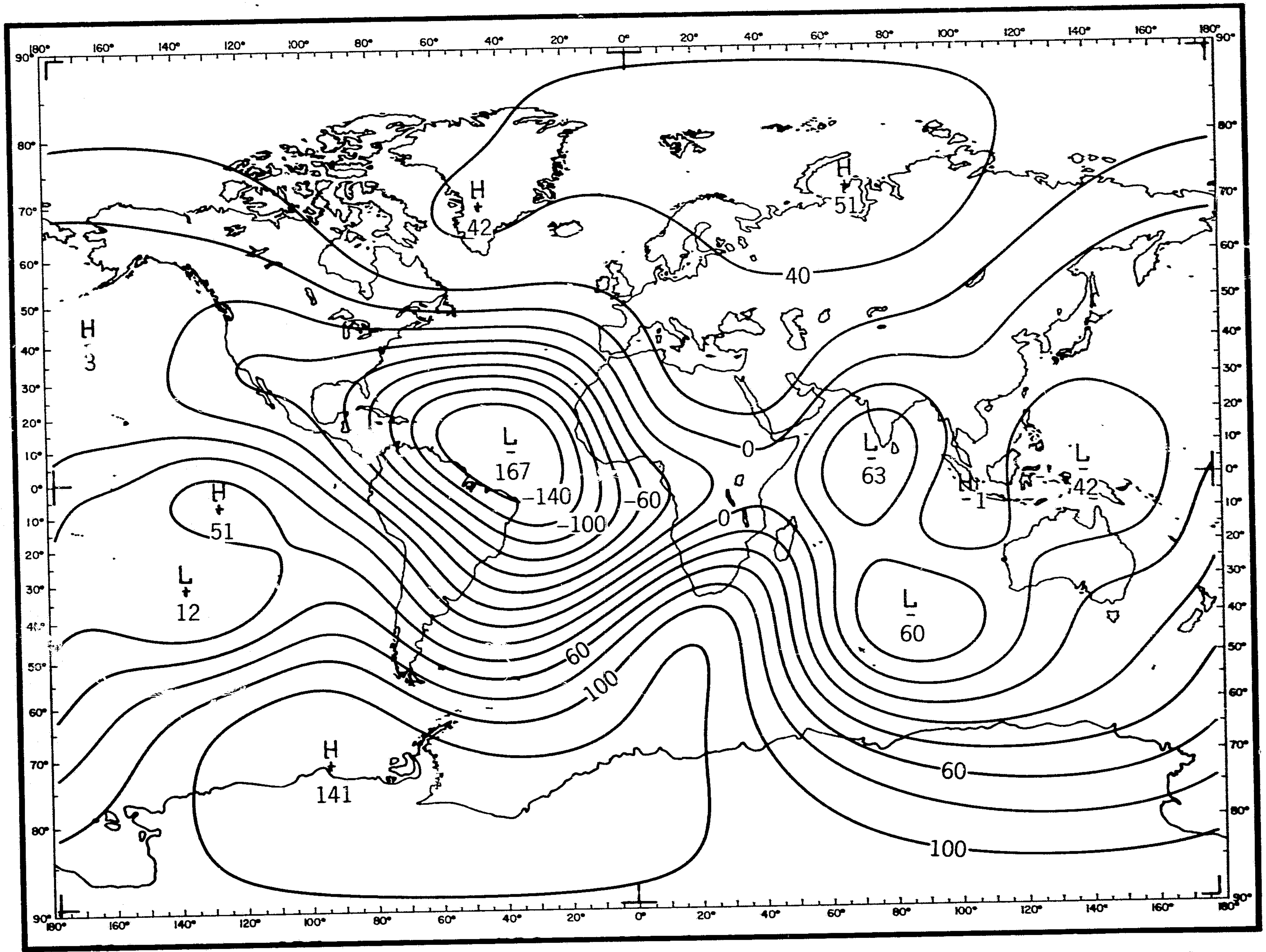
VERTICAL FORCE (gauss) Z



IGRF 1965.0

SECULAR CHANGE OF VERTICAL FORCE (gammas/year)

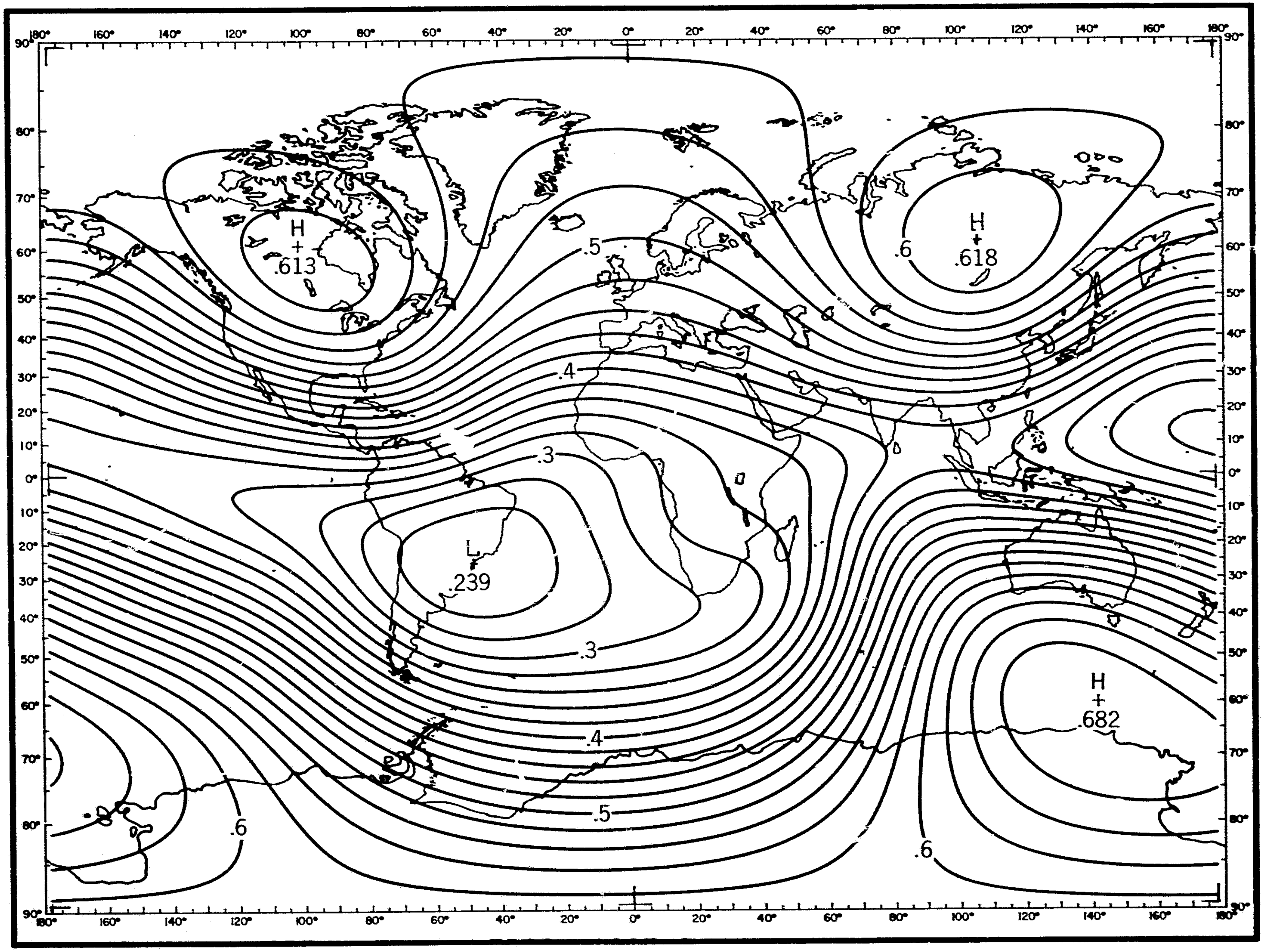
$\dot{Z}$



IGRF 1965

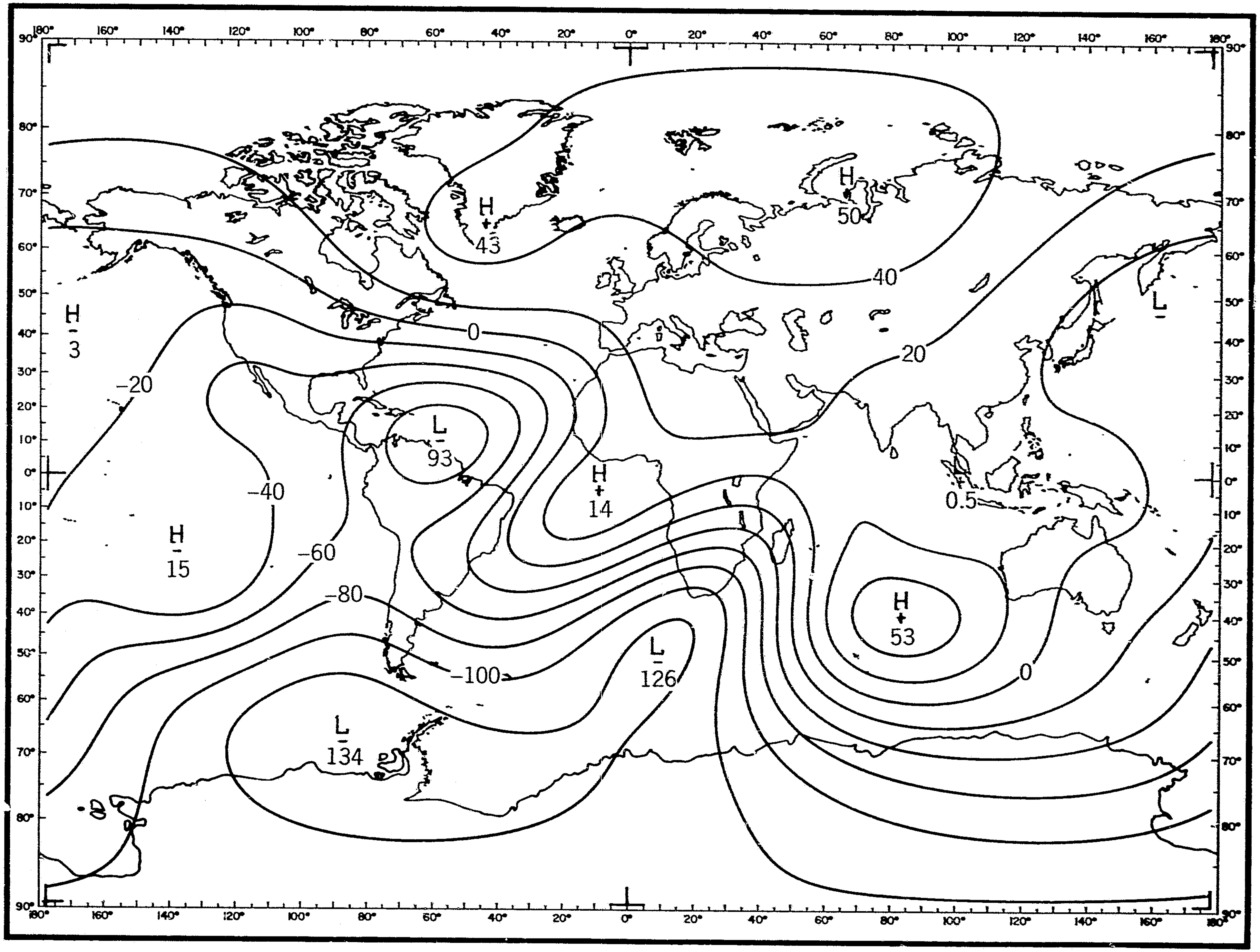
TOTAL FORCE (gauss)

F



IGRF 1965

SECULAR CHANGE OF TOTAL FORCE (gammas/year) $\dot{F}$



IGRF 1965

APPENDIX 2

Coefficient Normalization

All of the previous field derivations have arbitrarily set the earth's mean radius at 6371.2 for the value of a in the factors $(a/r)^{n+1}$ of the potential expansion. This value stemmed from the old standard earth constants with equatorial radius 6378.388 and flattening 1/297. However, the new constants have become 6378.15 and 1/298.25 respectively. Integrating

$$\bar{r} = \int_0^{\pi/2} r \cos\theta \, d\theta$$

we obtain $$\bar{r} = \frac{a}{m} \ln(m + a/b)$$

where $m = \sqrt{a^2 - b^2}/b$

a = equatorial radius, and

$b = a(1 - f)$ is the polar radius with f the flattening factor

The values with the old and new constants are as follows:

f	a	b	$\bar{r}$
297	6378.39	6356.91	6371.21
298.25	6378.16	6356.77	6371.02

APPENDIX 2
(cont'd)

I would like to recommend that for the sake of simplicity and to assure that we are not bound to constants of only historical significance, that we adopt the value of 6371 for a. This is a very slight change and has the effect of only altering the g_1^0 term from -30339 to -30342 and the h_1^1 term from 5758 to 5759. The constants α to make the correction $g = g' + \alpha g'$ where g' is the old values of g or h, are

n	$\alpha \times 10^5$
1	9
2	13
3	16
4	19
5	22
6	25
7	28
8	31
9	35
10	38
11	41
12	44

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